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CONDITION ASSESSMENT FOR SEISMIC EVALUATION

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ABSTRACT

An integrated methodology based on nondestructive dynamic field testing and system identification studies is suggested for reliable seismic condition assessment of actual constructed facilities. The seismic vulnerability is evaluated by field-calibrated comprehensive 3-D FE models developed by structural identification. Experimentally measured and analytically simulated modal flexibilities are correlated. These studies revealed our capabilities for evaluating seismic vulnerability or reliability of different types of structures. These efforts helped to identify and conceptualize a number of unresolved important issues that influence maintenance management and rehabilitation design in seismic regions.

KEYWORDS

Earthquake resistance; experimental test; nondestructive evaluation; structural analysis; system identification.

INTRODUCTION

Defects, premature aging, deterioration, damage, and natural hazards while in service cause inadequate performance of structures. The societal expectations of structural performance is always increasing. While it would be desirable to expect from a public facility, for example, a service life of 100 years, many continue to require extensive rehabilitation in only 20-40 years. Furthermore, it is realized that many regions, where seismic events were not considered as a design criterion, may be exposed to considerable seismic risk given a design life of 100 years. Therefore, civil engineers now confront the problem of assessing the reliability (or vulnerability) of existing constructed facilities and making management decisions regarding maintenance, rehabilitation, upgrading, or deconstruction. The awareness of structural performance, effective maintenance management, and reliable rehabilitation design is encouraging research related to innovative concepts and strategies in conjunction with technological advances in nondestructive experimental condition assessment, which are needed to improve the technical aspects of the state-of-the-practice in preservation.

Being able to establish the condition of an actual constructed facility, with possible defects, deterioration, and damage, is a most important challenge obstructing any necessary corrective actions. Condition assessment should be comprehensive, objective, and should lead to a quantitative and accurate assessment of the state-of-health in terms of structural reliability. Condition assessment should also provide an adequate basis for the design of effective maintenance management and reliable pre-earthquake retrofit or post-earthquake rehabilitation. In the past, the objectives of structural engineering analysis and design were to acquire a constructed facility with desirable performance. Limitations in our in-depth understanding of actual loading and response mechanisms did not matter as long as structures performed desirably. It is now realized that the actual real performance of structures can no longer be ignored in engineering practice, research, and education. The remaining issue is the capability of accurately observing, measuring, conceptualizing, and modeling actual structural behavior.

The hazard from earthquake loads on an existing structure may be estimated by vulnerability evaluation. Assessment of the vulnerability condition of a structure may be deduced by estimating its remaining strength. This may be provided by reliable diagnosis of the *as-is* response to a design earthquake or code-prescribed load input. Since the structure has been exposed to previous defects, deterioration, and damage, these are more likely only partly visual and mostly internal. Also, reliable manners of relating any visually observed local damage to the global behavior and capacities of the structure are lacking. Furthermore, full visual observation of defect, deterioration, and damage phenomena and their comprehension and characterization do not necessarily guarantee the engineered quantitative treatment of uncertainties for diagnostic purposes. Therefore, conventional diagnostic processes based on visual inspection and quasi-archeological interpretations of *as-built* design documents cannot provide the required level of engineered quantification and accuracy. Besides, human-based visual inspection and interpretations may considerably vary depending on the professional background or even mood of the particular individual.

Uncertainty also exists in assessing soil-structure interaction, load-bearing systems, secondary elements, and composite action or interaction between primary and secondary elements. Omitting these in design and evaluation may not be realistic for many real-life structures. Analysis alone, with simplifying assumptions, cannot provide reasonably reliable results for the distribution and redistribution of loads among all the resistance components participating in the global resistance. In certain constructed facilities, the measured real resistance contribution of secondary elements, nonstructural components, or components designed to resist only a certain structural function may reveal surprises to experienced design engineers. Comprehension of resistance components and mechanisms, their quantified relative contribution, and interaction may redirect future design and necessary management steps to maintain satisfactory structural response. Wherefore, more deterministic methods are required for reliable condition assessment of structures.

OBJECT

The actual seismic resistance of a newly-constructed structure and the load-carrying capacity of its different components and elements are known to the extent of the analytical design. Primary unknowns as design and construction defects with initial stresses and strains may dim the most sophisticated analysis and design turning out the as-built capacity unclear. Time-dependent deterioration mechanisms compounded with initial state and damage further reduce the reliability of the analytically determined design capacity. Post-earthquake seismic resistance evaluation of damaged structures for safety and socioeconomic decisions is even more obscure. In this paper, the process of condition assessment for the seismic capacity of existing structures is discussed by system modeling, modal testing, and identification studies.

METHODS

Prediction of Seismic Resistance

Reliable prediction of structural capacity is one of the three basic issues involved in the determination of the earthquake resistance, interrelated with load input and structural demand provided by seismic code provisions. In the last three decades, significant scientific and practical effort has been invested in the development of global and local behavior approaches, prediction theories, sophisticated computer programs, exploration of required seismic design load input, and the strength and ductility demand requirements of structures. However, besides the compared test specimens, the resulting theories and analytical approaches have failed to reliably predict the responses of real structures, particularly at ultimate limit states. Evaluation of demand and prediction of supply are not straightforward, especially in seismic design. Consequently, there has not been a corresponding improvement in our understanding of earthquake-resistant design. The assessment of a structural system's continuously variable condition remains questionable, whether the required procedure is to maintain or extend its degrading durability, due to local detailing, continuous loading, fatigue, material aging and deterioration, interactive effects with the changing environment, soil-structure interaction, interelement interaction, intermechanism interaction between resistance components, or earthquake attack.

Recognizing that there are many uncertainties in the actual procedures of supply estimation, one of the most effective ways to mitigate the destructive effects of earthquake disasters on structures is to develop better methods of structural evaluation. The method should incorporate global resistance mechanism appreciation and local damage detection probes for rehabilitaion design. Actual evaluation methods may be improved by theoretical, analytical calculations integrated with experimental field testing through instrumentation and monitoring. Seismic risk reduction philosophy should attempt to provide experimentally measured parameters for a reliable condition-assessment methodology, proper routine seismic vulnerability evaluation, and behavior analysis by means of field-calibrated analytical models.

Before further investigation of nonlinear approaches, it is now essential to reliably explore—through the proposed evaluation methodology, full linear appreciation of different structure types, their resistance components and mechanisms, their relative participation and variation at different loading stages, and their interaction. It has been shown by Hosahalli and Aktan (1994) that a complete and accurate, linearized, field-calibrated analytical model provides reliable seismic vulnerability assessment for retrofit design of buildings. In addition, this method helped to quantify the relative participation of different resistance components of bridges and the deck-beam composite action, which was incorrectly neglected for rating (Aktan *et al.*, 1995). This research has also shown that analytical models which have not been validated by structural field identification lead to critically erroneous renewal design conclusions. One can conduct linear or nonlinear sensitivity studies for seismic vulnerabilty evaluation and retrofit design by using the identified field-calibrated model as a starting point.

The engineering community have traditionally focused on "strength capacity" in new design and evaluation. Research reveals that considering strength, the structural performance may be likely higher than the design. However, considering serviceability, the performance might likely be lower than what is qualitatively expected (Aktan *et al.*, 1995). The relationship between material, element, and structural performance vs. time—considering any design and construction defects with initial stresses, deterioration, aging, and damage, is illustrated in Fig. 1.

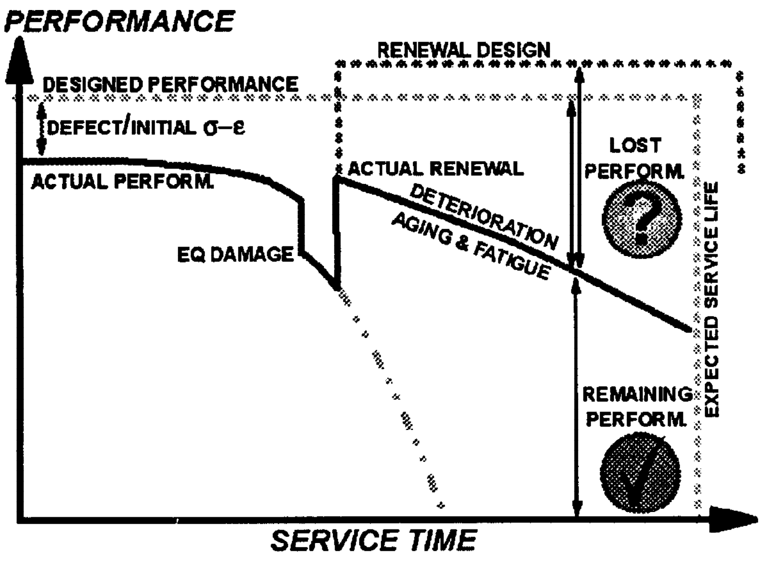

Fig. 1. Actual performance vs. time relationship

Condition Assessment

Actual condition assessment methods may be categorized as based on conventional approaches or system-identification approaches, as shown in Fig. 2. Conventional approaches may be classified as global or local. Condition assessment would include identifying any design, construction, or maintenance errors, as well as any local defects, deterioration, and damage—all visible or invisible, such that the global state of health, i.e. the structural reliability of the facility may be established for rational rehabilitation design. Damage is broadly defined as anomalous (as opposed to natural) changes in the state parameters that affect performance. Definitions for damage indices have been offered at the material, element, and structural levels. Specifically, damage is visible degradation of structural elements, reductions in the incremental element or structural stiffness, strength, or energy dissipation properties, and changes in the structural state properties compared to a baseline state. Some researchers have defined damage in the modal space, in terms of modal characteristics or derivatives such as changes in frequencies, displacement or strain mode shapes, or modal strain energy distribution (Shin and Hjelmstad, 1994, Stubbs *et al.*, 1995). Sanayei and Onipede (1991) hypothesize that element stiffness parameters of an analytical characterization, quantified through system-identification and parameter-identification techniques, can reveal damage. When damage and its identification is defined as such, it is clearly not possible to assess condition only visually, or even by instrumenting one or two members and conducting diagnostic load test.

SYSTEM-IDENTIFICATION APPROACH			CONVENTIONAL APPROACH		
Modal Identification	Numerical Identification	Geometrical Identification	Global	Local	

• Frequency
• Damping
• Mode shapes
	• Stiffness coefficients
	• Mass coefficients
	• Flexibility coefficients
	• Changes in frequencies, displacement, strain mode shapes
	• Modal strain energy distribution
	• Other derivatives
		• 3-D FEM:
		  • Microscopic
		  • Macroscopic
		  • Element level
		  • System level
		• Grid modeling:
		  • System level
			• Visual inspection
			• Proof-load test
			• Stationary/ moving load tests
			• Dynamic tests
				Quantitative	Qualitative

				• Measuring dimensions, deflections, damage • Material sampling and testing • Mechanical sampling and testing	• Visual inspection • X-ray • Impact echo • Acoustic imaging

Fig. 2. Classification of condition assessment methods

Condition assessment may be defined as measuring and evaluating the current state of a structure in terms of measurable dynamic structural properties such as frequencies, damping, and flexibility/stiffness. In addition to measuring these serviceability limit state dynamic characteristics, there is interest in estimating those characteristics which govern behavior at the damageability limit states. Additional critical parameters are toughness against fatigue, resistance to deterioration mechanisms, aging and stress-assisted aging, and most importantly, the available strength, deformability, and energy dissipation capacities under probable earthquake loads, and failure modes.

Dynamic Testing

Traditional types of dynamic testing for evaluating structural properties comprise: (1) Monitoring service-induced response with accelerometers; (2) ordinary modal test and check for modal parameters; and, (3) scientific modal test and check for changes in modal parameters. While experiment and direct interpretation attempts are not enough to determine reliability, modal test can be achieved in the context of system identification. This method includes rigorous modal test, process of modal parameters into flexibility, and use of flexibility as a means of diagnosing damage and deterioration by diagnostic load patterns. The prediction is performed by conducting simulation and calibration of an analytical model. The potential of scientifically performed modal testing processed into modal flexibility has been demonstrated to provide a good measure of damage and deterioration diagnostics.

It is clear that modal testing cannot diagnose damage and deterioration by direct interpretation of the test results. Furthermore, poorly performed modal testing with inferior equipment cannot lead to successful and reliable diagnostics. It is shown that if there is no baseline, flexibility can still be used to detect and diagnose possible anomalies. Yet, if there is a baseline, it becomes a far more definitive test of damage and deterioration. Modal testing is also an excellent tool that provides the flexibility and establishes better understanding of response mechanisms and behavior characteristics of structures. As structures are becoming more slender and flexible, determination of serviceability through deflection of existing structures is also developing as an issue to be solved by definitive and objective condition assessment methods.

System Identification

As indicated in Fig. 2, experimental modal analysis reveals the modal parameters such as frequencies, damping factors, and mode shapes, which in turn are used to estimate the stiffness matrix. The experimental stiffness matrix together with the modal parameters serve as indices for evaluating the performance and load capacity of the structure. Analytical FE modeling, as another system identification method, is used to obtain the exact mathematical model of the real structure to further simulate conditions that can not be simulated by any other method and to compare with future experimental results for integrity monitoring and damage detection purposes. Experimental modal parameters are then used to improve analytical models by correlating experimental and analytical mode shapes, frequencies, and deflection profiles.

Prior to actual testing of a structure, a procedure to obtain successful results must be devised. Such a procedure is especially important for testing large-scale structures, where factors like logistics, various constraints, and condition of the structure become very important. In view of the initial considerations, instrumentation, excitation, and exciter type are decided upon and modal test setup is finalized.

Swept-sine forced vibration test with the 900 lb linear mass exciter, exerting a 4.5 kips of moving force, overcomes the excitation limitations of impact testing. The data, in terms of acceleration, is acquired through digital signal processing software, which uses swept-sine measurement mode to characterize the nonlinearity and better excite the structure by energy concentration.

The bridges are instrumented with sensitive accelerometers that are designed to measure very low levels of vibrations. Since the major concern in condition evaluation is the vertical response of a bridge, all truss connections are instrumented first vertically, then horizontally in order to capture the three dimensional behavior that would incorporate the torsional effects.

Methodology

The structural identification methodology is formulated at the serviceability, fatigue, and ultimate limit states. The method has been designed to maximize the advantages of a number of experimental and analytical tools. The basic concepts of the methodology are: (1) Identification of the most important mechanisms that affect structural behavior at different limit states and their proper incorporation into design, inspection, evaluation, and maintenance management; (2) investigation of age and deterioration effects on these mechanisms; (3) verification of the possibilities to measure short-term and long-term structural behavior accurately, and to develop experimental condition-assessment techniques that would help to reliably establish the global state of health; (4) integration of hazard estimation with such an experimental condition-assessment procedure; and (5) development of analytical techniques that would reliably project the existing capacities of a structure and its remaining service life from the results of experimental condition assessment.

The comprehensive methodology should be designed and developed to integrate objective condition assessment with life-cycle maintenance management. This attempt develops a structural-identification methodology that integrates analytical modeling, experimental testing, and damage diagnostics into a rational framework. The methodology entails the following steps:

1) Compilation of structural database: Design and as-built documentation, and maintenance records.
2) Creation of preliminary linear and nonlinear 3-D FE model and analysis.
3) Design and performance of field instrumentation and monitoring setup, to effectively and reliably capture and identify the necessary state parameters with minimum sensors. Some backup sensors are also required for verification in case of bad data due to malfunctioning.
4) Design and performance of experimental modal test according to the FE analysis: Classify and group model parameters, study parameter sensitivity.
5) Post-processing of modal test data and parameter identification: Frequencies, damping coefficients, mode shapes, and flexibility.
6) Calibration of the FE model in the modal and flexibilty spaces, to simulate all captured critical global and local mechanisms.
7) Projection and quantification of structural capacity for prescribed seismic design load provisions.
8) Design and performance of effective maintenance, rehabilitation, or retrofit.

The methodology is summarized and schematized in Fig. 3, empasizing the analytical-experimental integration.

Step #	ANALYSIS	EXPERIMENT
1	Compile structural database	
2	Create preliminary FE model and analysis	
3	Design instrumentation & monitoring	Perform instrumentation & setup monitoring
4	Design modal test	Conduct modal test
5	Post-processing & parameter identification	
6	FEM calibration	
7	Calculate structural capacity	
8	Design maintenance & renewal	

Fig. 3. Seismic condition assessment methodology

The evaluation strategy is based on the concept of experimental modal multireference impact testing or closed-loop sweep testing. In general, the experiment will be conducted by modal multireference impact testing. In the case of flexible structures, closed-loop sweep-excitation testing is required. The tests in this study were conducted on highway bridges, instrumented by accelerometers in selected locations, chosen on the basis of an eigenvalue analysis of an a-priori model.

In the impact tests, input forces induced by an instrumented hammer and acceleration responses were measured. The frequency range of measurement was determined according to preliminary studies, to capture sufficient number of representative modes.

In the swept-sine testing, the structure was excited by linear inertia-mass actuators, especially developed for a servo-controlled excitation system. To obtain reasonably accurate data, the signal-to-noise ratio of the excitation should activate and measure the lower modes as well as the kinematics of hidden components as foundation rocking.

First modal testing and field-calibration of an analytical model accompanied with optimized system identification serves for reliable seismic vulnerability evaluation and as a reference baseline for damage detection and future comparisons. Post-earthquake seismic resistance evaluation is accomplished by re-performing the modal test and re-calibration of the existing model. Rehabilitation or replacement requirements for decision-making will be evaluated by comparison to the baseline model and condition assessment, which accurately identifies the location of the seismic damage and quantifies its extent. Occasional periodic testing is required for identification of environmental-attack related deterioration, stress-assisted aging, and fatigue-related degradation effects.

Successful implementations of the method to several constructed facilities to identify critical mechanisms and structural states were achieved. These constructed facilities included a 27-story flat-slab building, two multi-span steel stringer highway bridges, two multi-span reinforced concrete slab bridges, and two steel truss bridges (Aktan *et al.*, 1992, 1993a, b, and 1994a, b, c).

RESULTS

During the sweep, frequency-domain data was obtained from the accelerometers and the Frequency Response Functions (FRF) were calculated for all the responses. Modes of vibration (natural frequencies and damping factors) and residues (unscaled modal factors) were then extracted. Horizontal and vertical mode shapes were identified within the test frequency range. Relative movements of different components were observed.

In the impact tests, a sufficiently large number of frequencies and mass-normalized mode shapes were accurately experimentally measured. These were transformed directly into a *modal flexibility* matrix, defined as the accumulation of the contributions from modal vectors to flexibility. By activating all of the coefficients in the modal flexibility matrix through uniform loading and correlating the resulting deflections with the analytical model, deterioration and damage could be diagnosed.

The acquired frequency response function data are post-processed in the parameter estimation stage to obtain the modal properties, resonant frequencies, damping factors, and mode shapes. A major part of experimental modal analysis involves the extraction of resonant frequency ($\bar{\omega}_r$), modal damping (ζ_r), and residue (A^r) from frequency response data (H_{ik}). This procedure is referred to as parameter estimation, and involves a number of numerical operations in which a particular type of model is fit to the data and the best estimate of associated parameters is made. The Polyreference Time Domain (P.T.D.) complex exponential technique is used to obtain global least squares estimates of the modal properties, mode shapes, frequencies, and damping factors.

The residue vectors (mode shapes) estimated during post processing are then used to obtain modal vectors which in turn are used to obtain the flexibility matrix. The modal flexibility thus obtained has the signature of the structure inherent in its modal grid (e.g., nodes on the bridge). Applying any set of static loads to this grid, would result in deflections of the bridge. If any deflection profiles of the structure exist from static load tests, the modal flexibility can be verified with a comparison of the deflection profiles of both tests by loading the modal flexibility with a similar load pattern to the static load test. After the flexibility is verified, any kind of loading can be simulated to get the maximum deflections under various conditions (condition assessment).

Modal flexibility has been found to be a reliable tool in detecting damage (Aktan *et al.*, 1992). The flexibilities for both before damage (baseline) and after damage models are verified by static load test deflection comparisons. Then unit load and uniform load patterns are applied to the flexibility coefficients and the resulting deflections are evaluated one by one. Last of all, contributions of modes to flexibilities under these load patterns (participation factors) are evaluated for both global and local damage detection. Here, the margins of error are also defined so that any change can be reliably attributed to damage.

CONCLUSIONS

Conventional seismic evaluation techniques are liable to bias and supply only visual evidence, raising concern about the validity of the results. Analysis and inspection have inherent shortcomings, due to a variety of parameters, and are best controlled by system identification. The presented condition-assessment methodology leads to accurate measurement of state parameters, which have been shown to provide a sensitive index for identification of deterioration and damage, quantification of resistance mechanism contributions, and conclusively seismic evaluation of structures. Longterm observation of the suggested methodology will reorient design and renewal practice. Creative development of practical designs, suitable for evaluating longterm outcomes, should not omit the principles of controlled evaluation.

Comparison of experimentally measured and analytically synthesized dynamic properties revealed good correlation. Yet, it is obvious that errors arising due to faulty calibration during data acquisition cannot be detected by merely comparing synthesized and measured attributes. In order to ascertain the accuracy of the experimental results, it is essential to adopt a system identification strategy. The experimental and analytical methods must be planned so that the results of the process serve to complement each other for reliable condition assessment.

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